DISCLAIMER

GEOLOGICAL AND PETROPHYSICAL CHARACTERIZATION OF THE FERRON SANDSTONE FOR 3-D SIMULATION OF A FLUVIAL-DELTAIC RESERVOIR

(Contract No. DE-AC22-93BC14896)

Utah Geological Survey (UGS), Salt Lake City, Utah 84114

Submitted: April 1998

Contract Date: September 29, 1993

Anticipated Completion Date: July 31, 1998

Government Award (fiscal year): $32,025

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Reporting Period: January 1 - March 31, 1998

Objective

The objective of this project is to develop a comprehensive, interdisciplinary, and quantitative characterization of a fluvial-deltaic reservoir which will allow realistic inter-well and reservoir-scale modeling to be constructed for improved oil-field development in similar reservoirs world-wide. The geological and petrophysical properties of the Cretaceous Ferron Sandstone in east-central Utah will be quantitatively determined. Both new and existing data will be integrated into a three-dimensional representation of spatial variations in porosity, storativity, and tensorial rock permeability at a scale appropriate for inter-well to regional-scale reservoir simulation. Results could improve reservoir management through proper infill and extension drilling strategies, reduction of economic risks, increased recovery from existing oil fields, and more reliable reserve calculations. Transfer of the project results to the petroleum industry is an integral component of the project.

Summary of Technical Progress

Two activities continued this quarter as part of the geological and petrophysical characterization of the fluvial-deltaic Ferron Sandstone: (1) petrophysical analysis and (2) technology transfer.

Petrophysical Analysis

Subsurface geological interpretations, whether based on geophysical data or on drilling, can be anchored through case studies that combine stratigraphic concepts with transforms linking geological to geophysical variables. The primary goal of the petrophysical analysis task was to establish these transforms and their causal underpinnings. An essential aspect of this task was determining effects of diagenesis on petrophysics of the Ferron Sandstone. An additional objective was to examine the reliability of a common assumption: that geophysical properties and relationships observed in outcrop are representative of those operating in the deep subsurface. The possibility that the process that generates outcrop exposures, exhumation resulting from uplift and erosion, may overprint patterns of velocity, porosity, and permeability developed in the subsurface was examined. Petrophysical overprints potentially may result either from diagenetic processes or from mechanical rebound, the rock expansion caused by pressure release. In contrast to most previous studies of diagenetic influences on petrophysical properties, the emphasis here is on dissolution rather than on cementation.

In two field seasons (1994 and 1995), a total of 722 oriented core plugs from the Ferron outcrop were collected. The core samples were 1 to 3 inches (3-8 cm) long and 1 inch (2.5 cm) in diameter. Sampling was conducted along more than a dozen near-vertical outcrop traverses (Fig.1). A usual vertical sample spacing of 6.5 to 13 ft (2-4 m) targeted all major lithologic units. Petrophysical sampling during the third project year concentrated on drill cores, particularly those from the Ivie Creek drilling program. Eighty-six core plugs and 11 three-dimensional core plug sets were taken from Utah Geological Survey (UGS) Ivie Creek drill hole nos. 3, 9, and 11 (Fig. 1). Shale units in these drill cores were unweathered and therefore could be sampled, unlike outcrop shales. Of these plug samples, 471 were analyzed using the Geoscience Evaluation Module at Amoco.[1, 2]

This petrophysical study challenges the reliability of a common assumption: that geophysical properties and relationships observed in outcrop are representative of those in the deep subsurface. The processes that generate outcrop exposures (uplift, erosion, and exhumation) were found to overprint patterns of velocity, porosity, and permeability developed in the subsurface.

Thin-section examinations showed that little, if any, primary porosity appears to remain in any of the Ferron outcrop samples. A complex diagenetic history culminated with development of substantial secondary porosity by carbonate dissolution. This secondary porosity is intergranular, not vugular or crack porosity. Petrophysical measurements confirm that decreasing carbonate content is strongly associated with porosity increase. Surprisingly, clay-mineral content has only a minor direct correlation with petrophysical properties.

Ferron porosities in deep wells suggest that pre-exhumation porosities were 4±4%. Porosity increase accelerated as the Ferron was progressively exhumed. By the time portions of the Ferron reached near-surface depths, average porosity had increased to 9.3±2.4%, and outcrop samples are

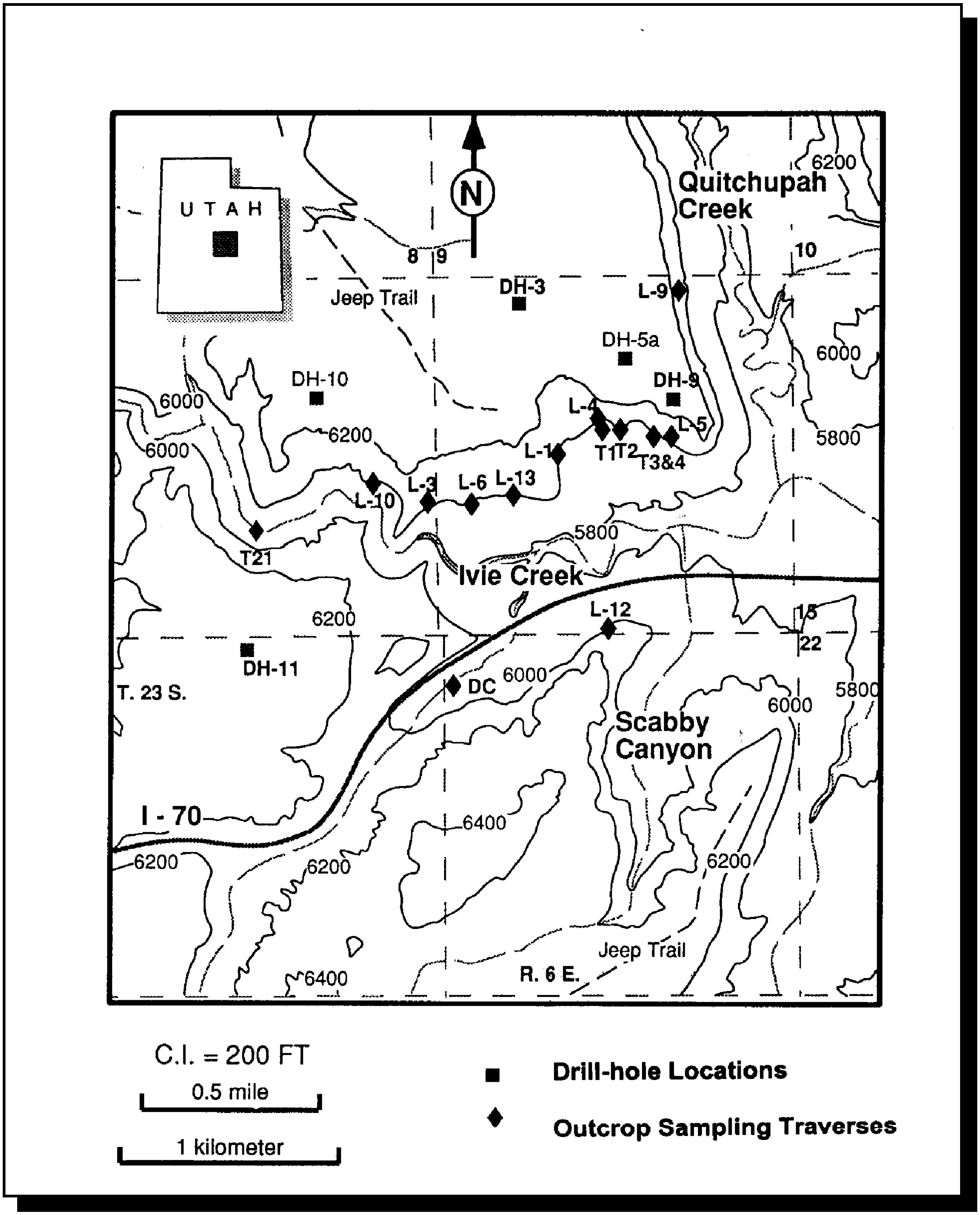

Fig. 1. Map of the Ivie Creek case-study area showing location of outcrop sampling traverses and UGS drill holes.

even more porous (13.0±0.6%). This pattern of secondary porosity development differs from the diagenetic pattern commonly observed in deeply buried, but not exhumed, sandstones: growth of secondary porosity below the depths at which primary porosity is destroyed. The Ferron Sandstone, like sedimentary rocks in several other foreland basins, appears to demonstrate the impact of meteoric flux on late-stage diagenetic history. Upward meteoric flux provides a combination of high flow rates and cooling-induced increase in calcite solubility that is probably responsible for late-stage carbonate dissolution within the Ferron Sandstone. The patterns of secondary porosity development seen in the study suggest that upward flow along the Ferron beds is pervasive and that this meteoric flow extends to depths of about 1.2 mi (2 km).

Whenever exhumation causes development of secondary porosity, then velocity decrease is also expected, because velocity is primarily dependent on porosity. Depth-dependent changes in both velocity and porosity are observed in well logs of the Ferron Sandstone. Cross plots indicate that the velocity drop at depths of <1800 ft (550 m) is even stronger than expected from the associated porosity drop (Fig. 2). Core-plug measurements indicate that the pressure dependence of velocity accounts for these log-based observations of changes in velocity and in velocity/porosity

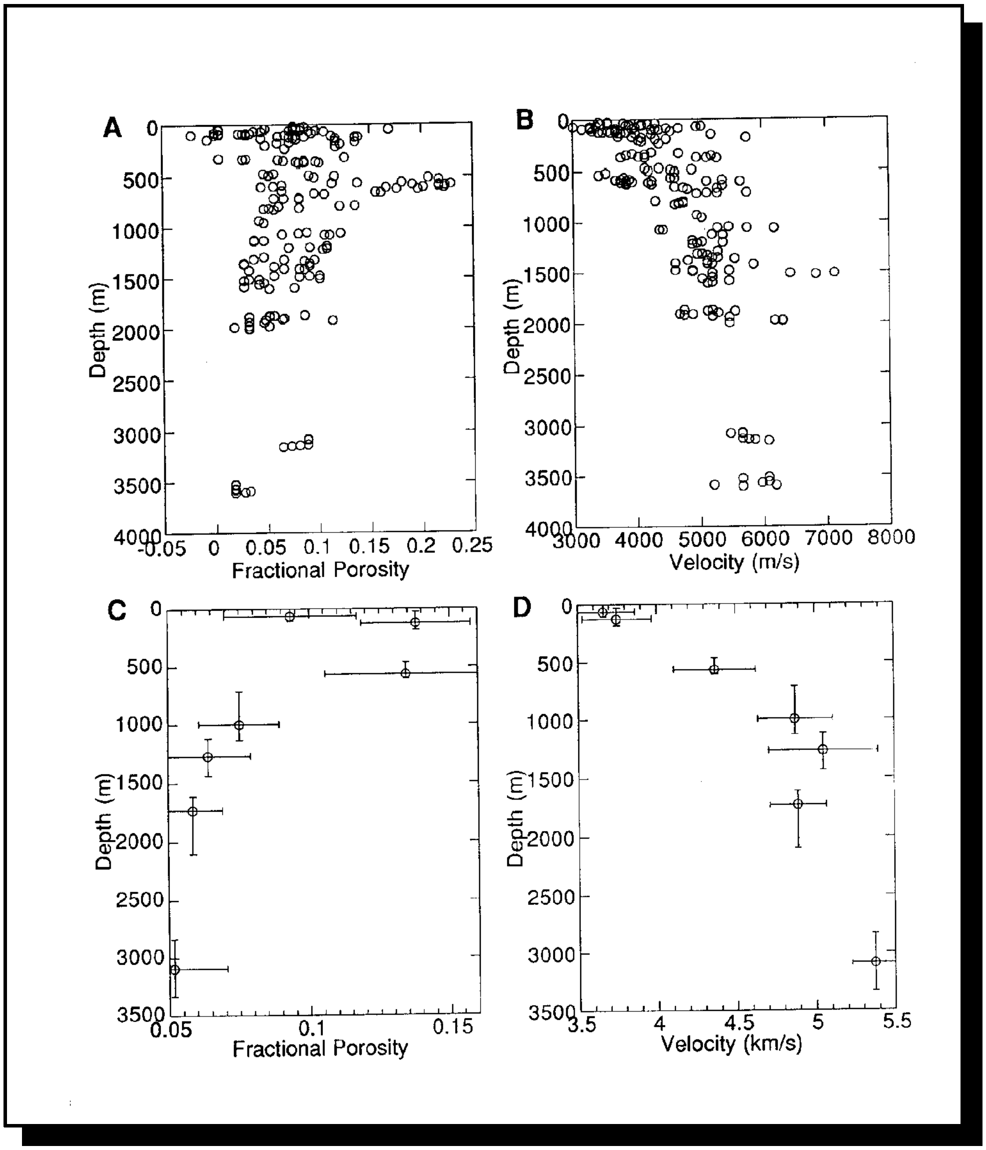

Fig. 2. Fractional porosity (A) and velocity (B) of individual Ferron beds, based on well logs from drill holes with locations plotted on Fig. 1. Note both the heterogeneity at a given depth and the systematic changes with depth. Variation of average Ferron porosity (C) and velocity (D) with depth, based on three-well adjacent-depth averaging of data from (A) and (B) respectively.

relationship. The lowest-pressure core-plug measurements have a velocity/porosity pattern similar to that for shallow (<1800 ft [550 m]) log data, and the highest-pressure core measurements are consistent with deep log data. Pressure decrease associated with exhumation has opened microcracks; laboratory velocity measurements at high pressure reverse this process.

Log analysts often generalize that sonic logs do not see secondary porosity, particularly vugular porosity in carbonates and fracture porosity. Among sandstones, however, the most common type of secondary porosity is that encountered by the Ferron logs: intergranular secondary porosity created by dissolution. Ferron core-plug velocity measurements and sonic logs clearly see this secondary porosity, responding in the same manner as for primary intergranular porosity. Comparison of whole-core and log measurements at UGS drill hole Ivie Creek No. 3 showed consistency for both density and velocity, indicating that these two measurement scales are equally sensitive to microfractures (Fig. 3).

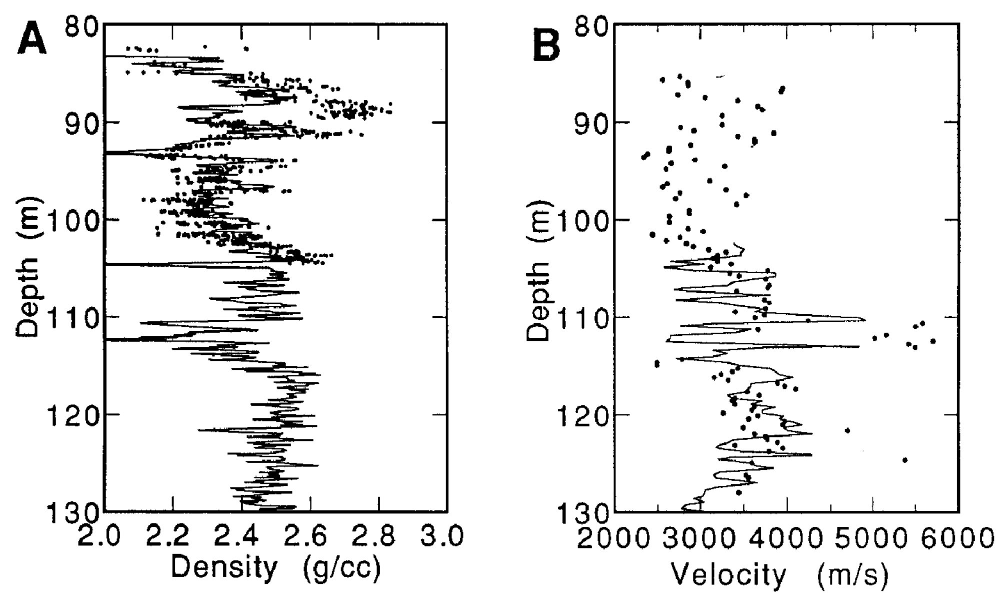

Fig. 3. Comparison of log (line) and core (dots) measurements for density (A) and velocity (B) at UGS Ivie Creek No. 3.

Permeability in the Ferron Sandstone is strongly dependent on porosity (Fig. 4). The effect of mineralogy on permeability is indirect, associated with the influence of grain size on porosity evolution. Grain size has affected the entire diagenetic history of the Ferron Sandstone; the coarsest sands retained highest permeabilities during compaction and cementation, and they experienced the greatest permeability enhancement during late-stage expansion of secondary porosity. At the scale of core plugs, permeability anisotropy is relatively minor.

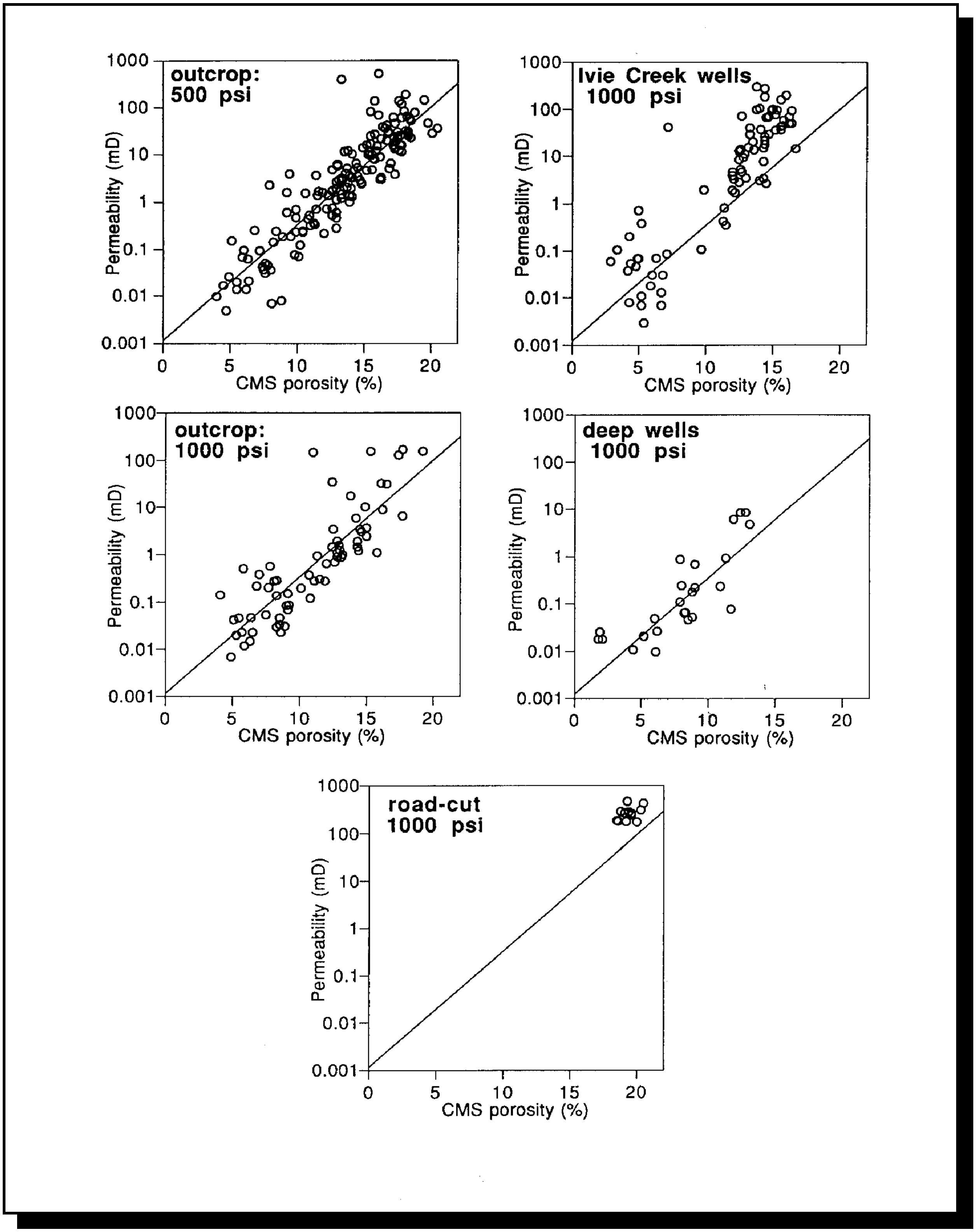

Fig. 4. Porosity/permeability pattern for core-plug samples from the Ferron Sandstone. The reference line is based on linear regression of the 500 psi (atmospheric pressure) outcrop data.

Technology Transfer

The UGS and its partners continued preparing to present results of the project to the petroleum industry as a three-day field trip and short course during the American Association of Petroleum Geologists (AAPG) annual national meeting in Salt Lake City, Utah, May 17-20, 1998. The field trip and short course will be sponsored by the UGS, National Petroleum Technology Office - DOE, Mobil Technology Company, and Amoco Production Company.

The pre-meeting field trip titled *Stratigraphic Framework for Reservoir Modeling in Fluvial-Deltaic Deposits: A Parasequence-level Analysis and Reservoir Characterization of the Ferron Sandstone, Utah,* is on May 14-16, 1998 (Fig. 5). The first day of the trip involves an introduction to the Ferron outcrops at Dry Wash, which affords an opportunity to view a variety of shoreline and fluvial depositional styles. The entire second day will be spent examining shoreface and delta-front deposits within three parasequences of the Kf-1 parasequence set in exposures along the walls of Indian Canyon. Most of the third day will be spent on outcrops north of Ivie Creek. The Kf-1 there includes river-dominated deltaic deposits in a well defined subdelta lobe. Overlying shoreface and wave-dominated deposits of Kf-2 will also be examined.

The short course titled *Core and Reservoir Modeling Workshop: Fluvial-Deltaic Nearshore Sands of Ferron Sandstone* will be offered during the AAPG meeting on May 17, 1998. The course will take the participants from outcrop to reservoir modeling and flow simulation results of the Ferron project. The course will begin with a brief review of the field stops and geologic setting. The morning will be devoted to observing core, corresponding geophysical logs, and core permeability data. Correlation exercises will help participants understand the challenges involved in working a subsurface data set, while enjoying the benefit of three-dimensional outcrop exposures. The afternoon the methods used to quantify the outcrop data, build two- and three-dimensional petrophysical models, and simulate different reservoir production scenarios will be outlined. Petrophysical and architectural data collected at the Ferron Sandstone study site were incorporated in project reservoir simulations that will aid in exploring the impact of clinoform architecture on fluid flow through a fluvial-dominated deltaic deposit. The simulation results provide direct insight into the way features observed in outcrop might influence reservoir production strategies. The detailed simulation models presented during the course also provide a basis for evaluating how such features might be treated in the upscaling methods needed to create the coarser simulation grids used in evaluating reservoir performance.

The UGS also released the January 1998 issue of *Petroleum News* featuring the Ferron Sandstone project. The project home page on the UGS Internet web site (http://www.ugs.state.ut.us/paradox.htm) was updated with the latest quarterly technical report and project publications list.

References

1. C. H. Sondergeld and C. S. Rai, A New Concept in Quantitative Core Characterization, *The Leading Edge*: 774-779 (July 1993).

2. C. H. Sondergeld and C. S. Rai, A New Exploration Tool: Quantitative Core Characterization, *PAGEOPH*, 141 (2/3/4): 249-268 (1993).

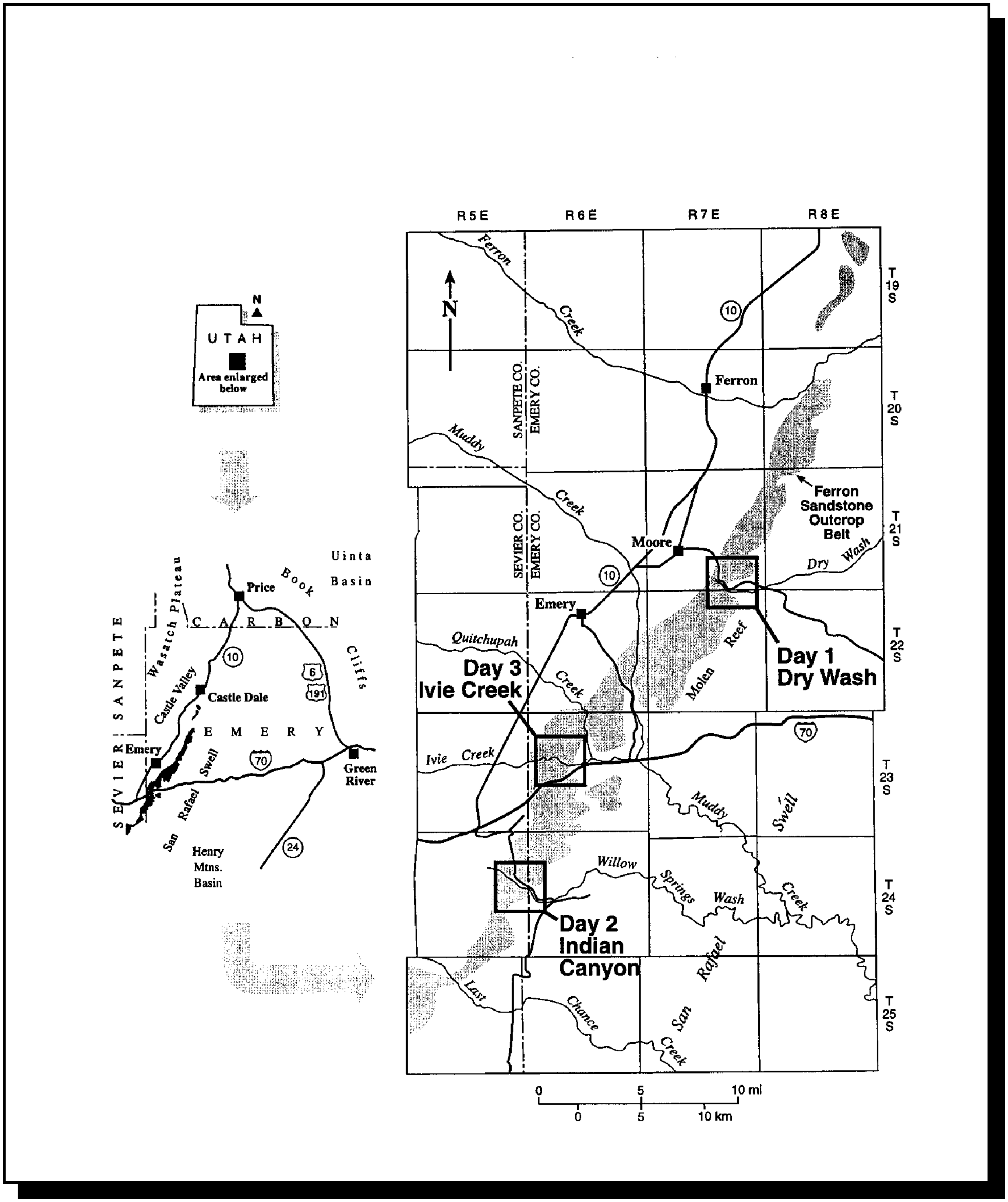

Fig. 5. Location map showing: the portion of the Ferron Sandstone outcrop belt (shaded) and American Association of Petroleum Geologists annual meeting field trip hike locations.